US009077306B2

(12) **United States Patent**
Kakinuma et al.

(10) **Patent No.: US 9,077,306 B2**
(45) **Date of Patent: Jul. 7, 2015**

(54) **MIXER HAVING FREQUENCY SELECTIVITY**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 89 days.

(21) Appl. No.: **14/114,383**

(22) PCT Filed: **Sep. 7, 2012**

(86) PCT No.: **PCT/JP2012/072834**
§ 371 (c)(1), (2), (4) Date: **Oct. 28, 2013**

(87) PCT Pub. No.: **WO2013/038993**
PCT Pub. Date: **Mar. 21, 2013**

(65) **Prior Publication Data**
US 2014/0057581 A1 Feb. 27, 2014

(30) **Foreign Application Priority Data**
Sep. 16, 2011 (JP) 2011-202507

(51) **Int. Cl.**
H04B 1/26 (2006.01)
H03H 7/01 (2006.01)
H03D 7/00 (2006.01)
H01L 43/08 (2006.01)

(52) **U.S. Cl.**
CPC ***H03H 7/0184*** (2013.01); ***H03D 7/00*** (2013.01); *H01L 43/08* (2013.01)

(58) **Field of Classification Search**
CPC H04B 2001/0491; H04B 1/26
USPC .... 331/96, 177 R; 455/191.1, 192.1, 20, 455/22, 118, 189.1, 190.1, 323, 326; 327/113, 116, 119, 355
See application file for complete search history.

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(74) *Attorney, Agent, or Firm* — Oliff PLC

(57) **ABSTRACT**

In order to provide a mixer capable of extracting a high multiplication signal and which has a reception band-pass filter function, a magnetoresistance effect element is provided that includes a pinned magnetization layer, a free magnetization layer, and a non-magnetic spacer layer disposed between the pinned magnetization layer and the free magnetization layer. This allows for a frequency converter which implements a desired band-pass filter by controlling a magnetic field applied by a magnetic-field applying unit to be provided.

8 Claims, 6 Drawing Sheets

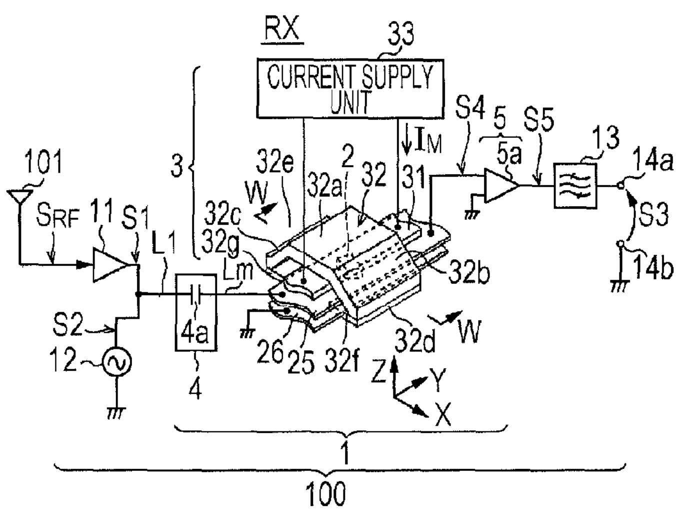

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FIG. 1

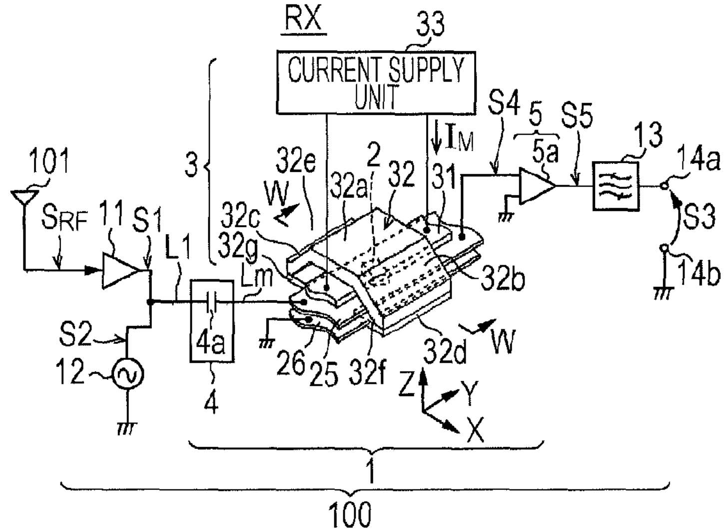


FIG. 2

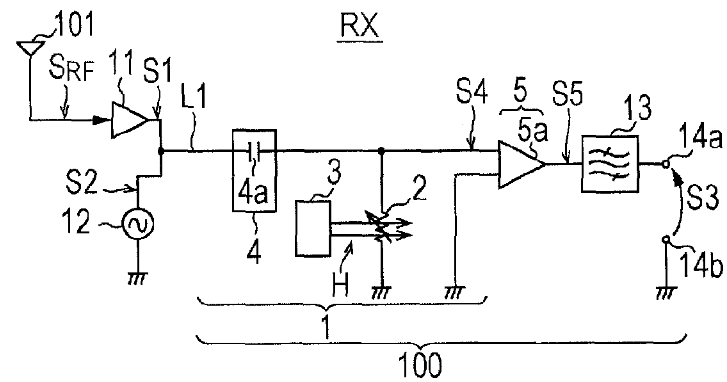


FIG. 3

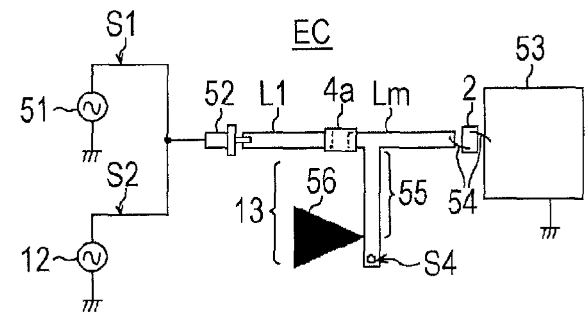


FIG. 4

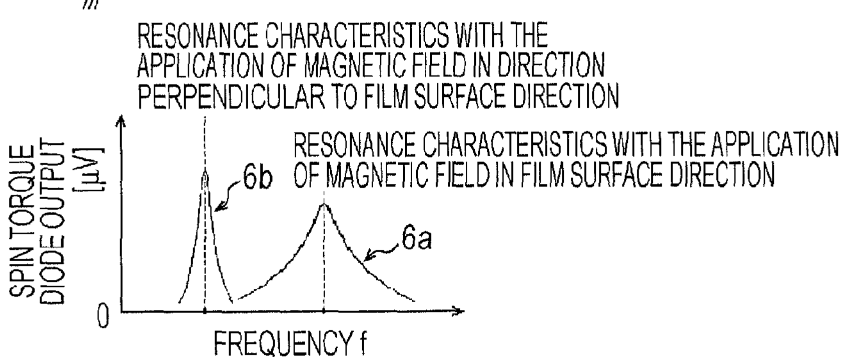


FIG. 5

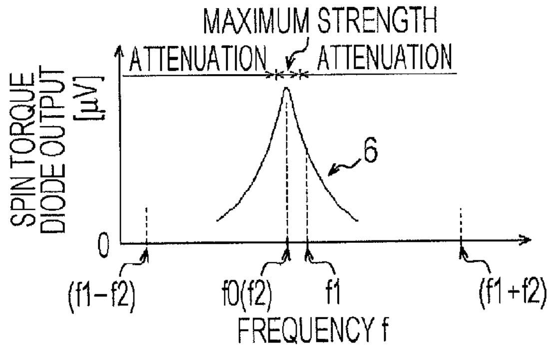


FIG. 6

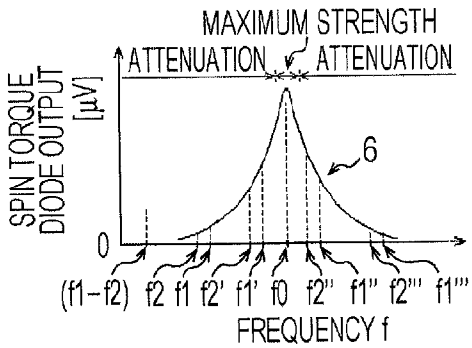


FIG. 7a

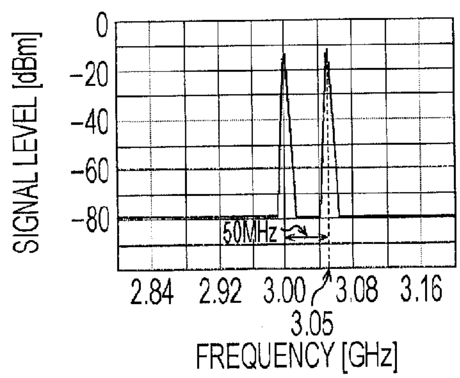


FIG. 7b

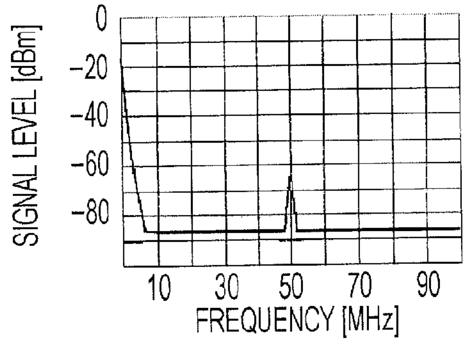


FIG. 8a

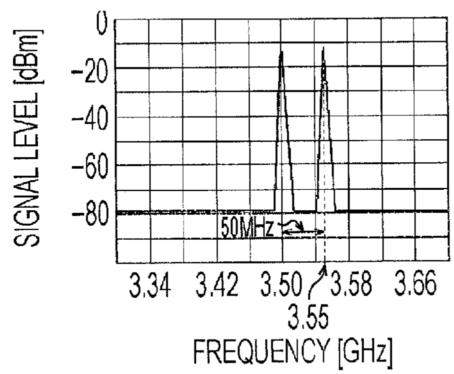


FIG. 8b

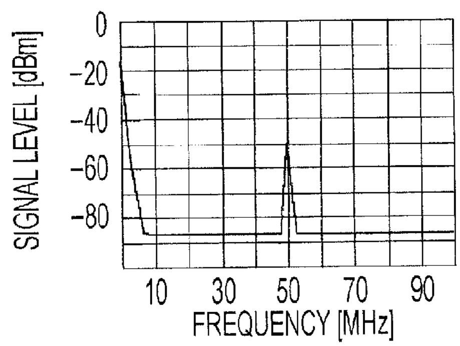


FIG. 9a

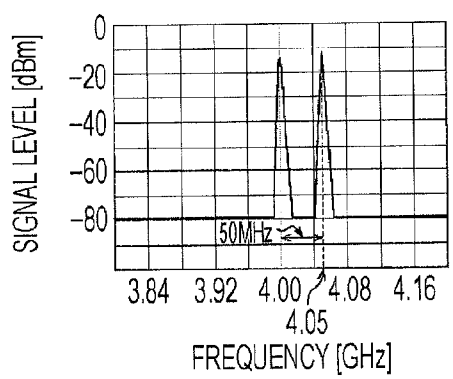


FIG. 9b

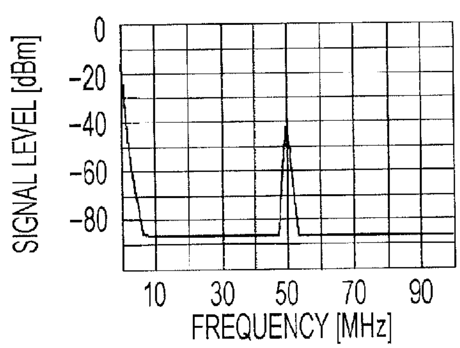


FIG. 10a

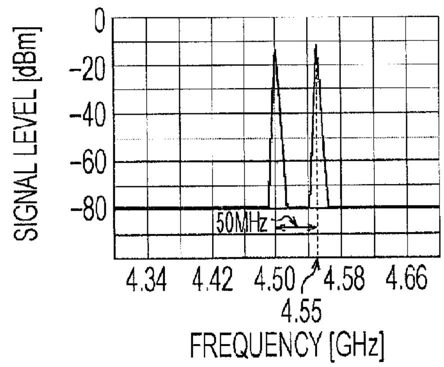


FIG. 10b

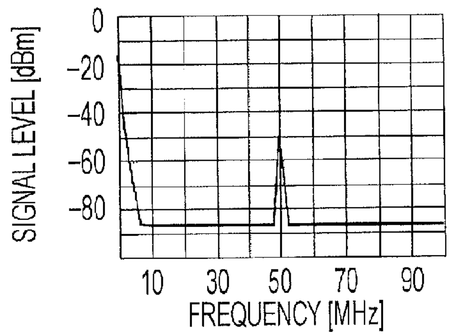


FIG. 11

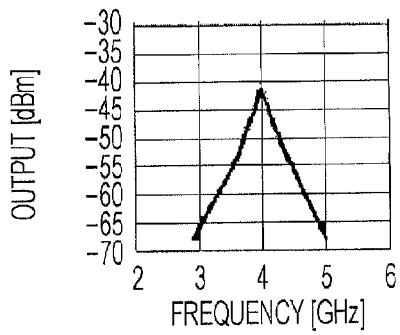


FIG. 12

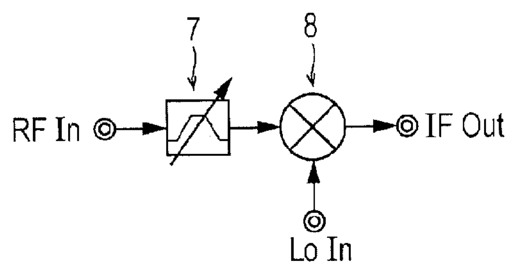


FIG. 13

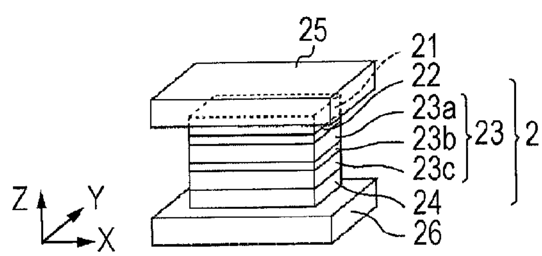


FIG. 14

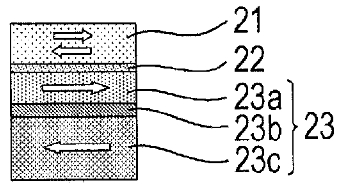


FIG. 15a

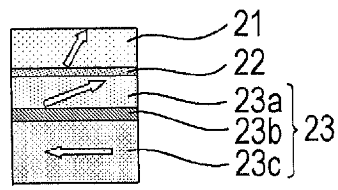


FIG. 15b

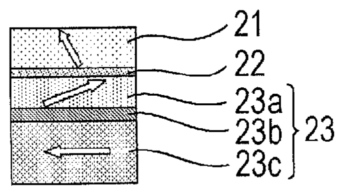


FIG. 16

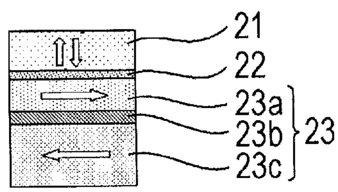


FIG. 17

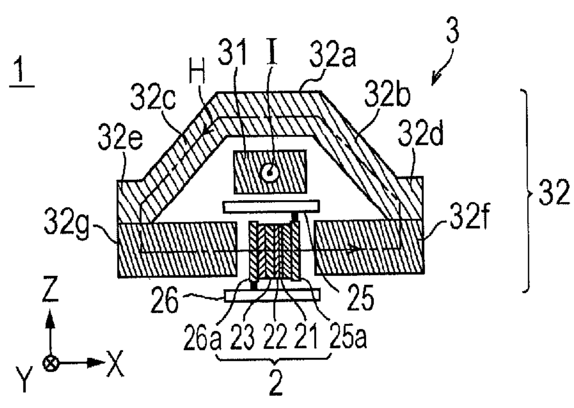


FIG. 18

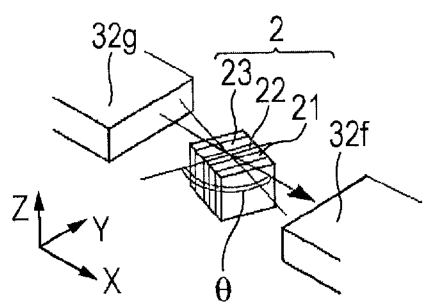


FIG. 19

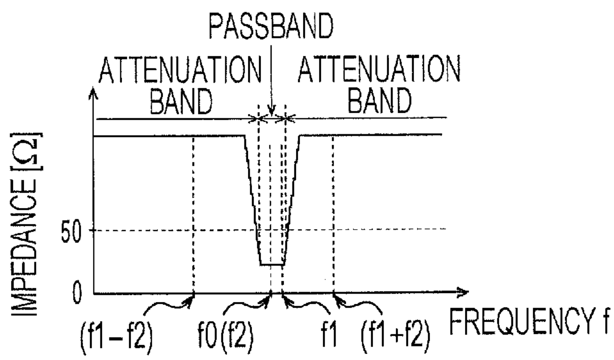
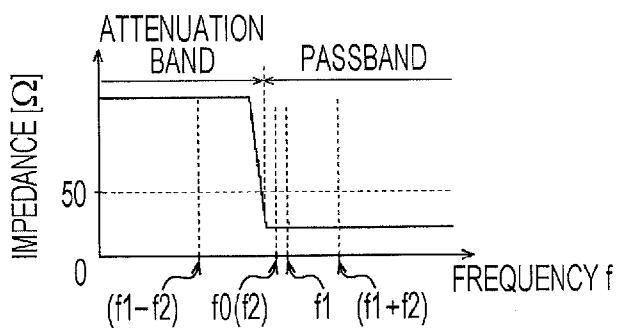

PASSBAND
ATTENUATION BAND
ATTENUATION BAND
IMPEDANCE [Ω]
50
0
(f1−f2)
f0(f2)
f1
(f1+f2)
FREQUENCY f

FIG. 20


ATTENUATION BAND
PASSBAND
IMPEDANCE [Ω]
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0
(f1−f2)
f0(f2)
f1
(f1+f2)
FREQUENCY f

MIXER HAVING FREQUENCY SELECTIVITY

TECHNICAL FIELD

The present invention relates to a mixer for generating multiplication signals by using a magnetoresistance effect element.

BACKGROUND ART

These days, frequency bands allocated to wireless communication are becoming saturated. As measures to deal with this situation, dynamic access concept, which is referred to as "radio opportunistic system (radio-opportunistic)" or "cognitive communication", is being studied. The principle of this concept is to analyze a frequency spectrum, to avoid a busy occupied frequency bandwidth, to identify and determine an available non-occupied frequency bandwidth, and to change the communication method. However, in order to implement this dynamic frequency access, an ultra-wideband oscillator and a tunable filter are required.

Generally, the reception performance (sensitivity and selectivity) of portable terminals is dependent on a frequency selective attenuator having frequency selectivity (band-pass filter) and a mixer. In particular, in order to effectively utilize frequency bandwidths and to implement energy-saving radio telecommunication, a band-pass filter having a high Q factor (Q factor indicates the state of resonance, and as the Q factor is higher, the resonance is more stable) is demanded. As the requirements for a tunable filter, the center frequency can be shifted, and control for increasing or decreasing the passband is necessary. At present, existing oscillation resonators, such as SAW (Surface Acoustic Wave: surface acoustic wave element, and more specifically, a filter element utilizing surface acoustic waves propagating on the surface of a piezoelectric body) and BAW (Bulk Acoustic Wave: a filter element utilizing resonant oscillation of a piezoelectric film itself called bulk acoustic waves) do not satisfy such requirements for a tunable filter. On the other hand, however, a compact tunable band-pass filter which can be fit in a portable terminal has not yet been realized.

As a magnetoresistance effect element, a TMR (Tunnel Magnetoresistive) element is known in which a spacer layer formed of a non-magnetic material is interposed between a pinned magnetization layer and a free magnetization layer. In this TMR element, when a current flows, spin polarized electrons flow and the orientation of magnetization (the orientation of electron spin) of the free magnetization layer changes in accordance with the number of spin polarized electrons stored within the free magnetization layer. In the free magnetization layer disposed in a fixed magnetic field, when the orientation of magnetization is changed, torque acts on electron spin so that the orientation of magnetization will restore to a stable direction constrained by the magnetic field, and oscillation called spin precession occurs when electron spin is oscillated by a specific force.

Recently, the following phenomenon was discovered. When a high-frequency AC current flows into a magnetoresistance effect element, such as a TMR element, strong resonance occurs (spin torque ferromagnetic resonance) when the frequency of the AC current flowing in a free magnetization layer coincides with the number of oscillations of spin precession in which electron spin is returned to the orientation of magnetization (see NPL 1). Moreover, a magnetoresistance effect element is known to exhibit the following function under the following situation. A static magnetic field is externally applied to a magnetoresistance effect element, and the direction of this static magnetic field is tilted within a pinned magnetization layer at a certain angle with respect to the direction of the magnetization of the pinned magnetization layer. In this state, when an RF current (RF current having a frequency which coincides with the number of oscillations of spin precession (resonant frequency)) is input into the magnetoresistance effect element, the magnetoresistance effect element is known to exhibit a function of generating a DC voltage proportional to the square of the amplitude of the input RF current across the magnetoresistance effect element. That is, the magnetoresistance effect element exhibits a square law detecting function (spin torque diode effect). It is also known that this square law detection output of the magnetoresistance effect element exceeds a square law detection output of a semiconductor pn junction diode under certain conditions (see NPL 2).

The applicant of this application has focused on the square law detecting function of a magnetoresistance effect element and studied the application of such a magnetoresistance effect element to a mixer which is operable with low local power, and has already proposed such a mixer (see PTL 1). A mixer using a magnetoresistance effect element includes a magnetic-field applying unit that applies a magnetic field to the above-described free magnetization layer, and when a first high frequency signal **S1** and a second high frequency signal **S2** for a local signal are input, the mixer generates a multiplication signal **S4** due to a magnetoresistance effect. However, the multiplication signal **S4** considerably attenuates if it directly passes through a 50-Ω matching circuit. Accordingly, the applicant of this application has proposed that an impedance circuit (a filter, a capacitor, or an active element) is inserted between an input transmission line through which the first high frequency signal **S1** and the second high frequency signal **S2** are transmitted and the above-described magnetoresistance effect element so that the impedance for the multiplication signal **S4** will become higher than the impedance for the first high frequency signal **S1** and the second high frequency signal **S2** (see PTL 2).

Although the characteristics of a mixer using the above-described magnetoresistance effect element are known, a high frequency device that can apply such characteristics to an industrial use is still unknown. Accordingly, the discovery of the application of such characteristics to an industrial use has been expected. The applicant of this application has found that, by using the square law detecting function of a magnetoresistance effect element, a multiplication signal output increases and decreases in accordance with resonance characteristics and the frequency selective function is exhibited. However, a high Q factor has not been obtained, and the frequency selection range is too wide, and thus, the applicant of this application has not yet found the application of the above-described characteristics to an industrial use.

CITATION LIST

Non Patent Literature

NPL 1: Nature, Vol. 438, 17 Nov. 2005, pp. 339-342
NPL 2: Magnetics Japan, Vol. 2, No. 6, 2007, pp. 282-290
PTL 1: Japanese Unexamined Patent Application Publication No. 2009-246615
PTL 2: Japanese Unexamined Patent Application Publication No. 2010-278713

SUMMARY OF INVENTION

Technical Problem

As a result of continuously conducting study of the above-described mixer, the applicant of this application has found that a square law detection output (signal level of a multiplication signal in the mixer) obtained due to the magnetoresistance effect is largely dependent on resonance characteristics of a magnetoresistance effect element. It is expected that the level of a multiplication signal will be increased if the Q factor of the resonance characteristics is increased, and at the same time, the performance of a filter with improved frequency selectivity is also expected for an industrial application. However, there is a technical problem that a mixer having a high-precision reception band-pass filter function has not been obtained.

The present invention has been made in order to solve the above-described problem. It is a major object of the present invention to provide a mixer having a frequency selective attenuator (hereinafter also called "band-pass filter") function which is implemented by obtaining resonance characteristics having a Q factor of 100 or higher while preventing a decrease in an output of a multiplication signal.

Solution to Problem

In order to achieve the above-described object, a mixer according to the present invention includes: a magnetoresistance effect element that includes a pinned magnetization layer, a free magnetization layer, and a non-magnetic spacer layer disposed between the pinned magnetization layer and the free magnetization layer, and that generates, in response to an input of a first high frequency signal **S1** and a second high frequency signal **S2** for a local signal, a multiplication signal by multiplying both the high frequency signals by each other using a magnetoresistance effect; a magnetic-field applying unit that applies a magnetic field to the free magnetization layer; and a frequency selective attenuator that exhibits its frequency selectivity for the multiplication signal by using the maximum strength of the multiplication signal generated when a resonant frequency f**0** of the magnetoresistance effect element is set to coincide with the frequency f**2** of the second high frequency signal **S2** for a local signal and when the frequency f**1** of the first high frequency signal **S1** is set to be near the frequency f**2** and by using attenuation of the multiplication signal generated when the first frequency f**1** deviates from the frequency f**2**.

In the mixer according to the present invention, there may be provided the frequency selective attenuator that exhibits frequency selectivity for the multiplication signal by using, when the resonant frequency f**0** of the magnetoresistance effect element is maintained at a fixed value by applying a constant magnetic field by the magnetic-field applying unit and when the frequency f**2** of the second high frequency signal **S2** for a local signal is set to be near the resonant frequency f**0** of the magnetoresistance effect element and the frequency f**1** of the first high frequency signal **S1** is set to be near the frequency f**2**, attenuation of the multiplication signal generated when the frequency f**1** and the frequency f**2** of the high frequency signals deviate from the resonant frequency f**0** of the magnetoresistance effect element.

In the mixer according to the present invention, the magnetoresistance effect element and the magnetic-field applying unit may be located so that an angle of the magnetic field generated by the magnetic-field applying unit with respect to the free magnetization layer of the magnetoresistance effect element will be an angle tilted in a range of 5° to 175° from a direction of the film surface toward a direction perpendicular to the direction of the film surface.

The mixer according to the present invention may further include: an impedance circuit in which impedance for the multiplication signal is higher than impedance for the first high frequency signal and the second high frequency signal for a local signal, the impedance circuit being disposed between an input transmission line through which the first high frequency signal and the second high frequency signal for a local signal are transmitted and the magnetoresistance effect element, the impedance circuit being constituted by a first filter in which the frequencies of the first high frequency signal and the second high frequency signal for a local signal are included in a passband and frequencies of the multiplication signal are included in an attenuation band, the first filter being constituted by a capacitive element or an active element in which self-resonant frequency band is set to be the passband; and an impedance conversion circuit that inputs the multiplication signal and outputs the multiplication signal with output impedance which matches characteristic impedance of an output transmission line to the output transmission line, input impedance being set to be a value higher than a value of the output impedance.

In the mixer according to the present invention, a multiplication signal generated by a square law detection operation (mixing operation) using a magnetoresistance effect exhibits a signal strength in accordance with resonance characteristics, and exhibits an attenuation curve in which the maximum peak of the multiplication signal is positioned at the same frequency as that when resonance characteristics are maximized. The presence of this attenuation curve has the same effect as that when a band-pass filter is inserted into an input terminal or an output terminal of the mixer.

In the mixer according to the present invention, a magnetic field generated by the magnetic-field applying unit is applied to the free magnetization layer of the magnetoresistance effect element by tilting an angle of the magnetic field in a range of 5° to 175° from the film surface direction toward a direction perpendicular to the film surface direction. With this arrangement, the magnetoresistance effect element is able to obtain resonance characteristics having a high Q factor and to extract a high multiplication signal. The attenuation curve of the multiplication signal becomes narrower, and thus, the frequency selectivity of the band-pass filter function can be improved.

In the mixer of the present invention, the first high frequency signal and the second high frequency signal can be output to the magnetoresistance effect element with only a small attenuation through an impedance circuit providing low impedance. Accordingly, in the mixer, a multiplication signal can be output by multiplying the first high frequency signal by the second high frequency signal for a local signal with smaller power. As a result, power saving can further be enhanced. Additionally, the impedance circuit provides high impedance in a frequency band of a multiplication signal generated by the magnetoresistance effect element, thereby preventing a decrease (attenuation) in the multiplication signal generated by the magnetoresistance effect element.

In the mixer of the present invention, the impedance circuit is constituted by a first filter in which the frequencies of the first high frequency signal and the second high frequency signal are included in a passband and frequencies of the multiplication signal generated by the magnetoresistance effect element are included in an attenuation band. Accordingly, the first filter can be constituted by passive elements. Thus, power saving can further be enhanced than when the impedance circuit is constituted by active elements.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a diagram illustrating a configuration of a frequency converter **100**.

FIG. **2** is an equivalent circuit diagram of a mixer **1**.

FIG. **3** is a diagram of an evaluation system including an evaluation based circuit board for evaluating the mixer **1**.

FIG. **4** illustrates the relationship between resonance characteristics of a magnetoresistance effect element **2** obtained when a magnetic field H is applied in a film surface direction and those obtained when the magnetic field H is applied in a direction perpendicular to the film surface direction.

FIG. **5** shows resonance characteristics of the magnetoresistance effect element **2** obtained when a magnetic field H applied to the magnetoresistance effect element **2** is maintained at a fixed value and spectrum waveforms of a first high frequency signal S**1** (frequency f**1**) and a second high frequency signal S**2** (frequency f**2**) for a local signal within a region of a resonant frequency f**0** of the resonance characteristics, and illustrates the relationships between the frequencies and the resonance characteristics when f**2** is fixed to 4 GHz and f**1** takes values near 3 GHz, 3.5 GHz, 4 GHz, and 4.5 GHz.

FIG. **6** shows resonance characteristics of the magnetoresistance effect element **2** obtained when a magnetic field H applied to the magnetoresistance effect element **2** is maintained at a fixed value and spectrum waveforms of a first high frequency signal S**1** (frequency f**1**) and a second high frequency signal S**2** (frequency f**2**) for a local signal within a region of a resonant frequency f**0** of the resonance characteristics, and illustrates the relationships between the frequencies and the resonance characteristics when f**1** and f**2** take values of 3 GHz and 3.05 GHz, respectively, 3.5 GHz and 3.55 GHz, respectively, 4 GHz and 4.05 GHz, respectively, and 4.5 GHz and 4.55 GHz, respectively.

FIG. **7***a* shows a spectrum waveform of a 3 GHz signal S**1** and a 3.05 GHz local signal S**2**.

FIG. **7***b* shows a spectrum waveform of a voltage signal (multiplication signal) S**4** when a 3 GHz signal S**1** and a 3.05 GHz local signal S**2** are input.

FIG. **8***a* shows a spectrum waveform of a 3.5 GHz signal S**1** and a 3.55 GHz local signal S**2**.

FIG. **8***b* shows a spectrum waveform of a voltage signal (multiplication signal) S**4** when a 3.5 GHz signal S**1** and a 3.55 GHz local signal S**2** are input.

FIG. **9***a* shows a spectrum waveform of a 4 GHz signal S**1** and a 4.05 GHz local signal S**2**.

FIG. **9***b* shows a spectrum waveform of a voltage signal (multiplication signal) S**4** when a 4 GHz signal S**1** and a 4.05 GHz local signal S**2** are input.

FIG. **10***a* shows a spectrum waveform of a 4.5 GHz signal S**1** and a 4.55 GHz local signal S**2**.

FIG. **10***b* shows a spectrum waveform of a voltage signal (multiplication signal) S**4** when a 4.5 GHz signal S**1** and a 4.55 GHz local signal S**2** are input.

FIG. **11** shows a spectrum waveform of an attenuation curve (band-pass filter) of a voltage signal (multiplication signal) S**4** with respect to the frequency of a signal S**1** when the magnetic field H applied to the magnetoresistance effect element **2** is maintained at a fixed value.

FIG. **12** is an equivalent circuit diagram of a band-pass filter function and a mixer function of the magnetoresistance effect element **2** when the magnetic field H applied to the magnetoresistance effect element **2** is maintained at a fixed value.

FIG. **13** is a perspective view of an area near the magnetoresistance effect element **2** (TMR element).

FIG. **14** illustrates magnetization directions of a free magnetization layer **21** and a pinned magnetization layer **23** of the magnetoresistance effect element **2** which are magnetized in in-plane directions according to the present invention.

FIG. **15***a* illustrates magnetization directions of the free magnetization layer **21** and the pinned magnetization layer **23** of the magnetoresistance effect element **2** when a magnetic field H is applied to the magnetoresistance effect element **2**.

FIG. **15***b* illustrates magnetization directions of the free magnetization layer **21** and the pinned magnetization layer **23** of the magnetoresistance effect element **2** when a magnetic field H is applied to the magnetoresistance effect element **2**.

FIG. **16** illustrates magnetization directions of the free magnetization layer **21** and the pinned magnetization layer **23** of the magnetoresistance effect element **2** which are magnetized in directions perpendicular to a layer plane direction according to the present invention.

FIG. **17** is a sectional view, taken along line W-W of FIG. **1**, of the magnetoresistance effect element **2** magnetized in directions perpendicular to a layer plane direction according to the present invention.

FIG. **18** is a perspective view of an area near the magnetoresistance effect element **2** and bottom magnetic bodies **32***f* and **32***g*.

FIG. **19** is a conceptual diagram illustrating impedance characteristics of an impedance circuit **4**.

FIG. **20** is a conceptual diagram illustrating impedance characteristics of a high-pass filter forming the impedance circuit **4**.

DESCRIPTION OF EMBODIMENTS

An embodiment of a mixer and a frequency converter will be described below with reference to the drawings.

First, the configuration of a mixer **1** and the configuration of a frequency converter **100** including the mixer **1** will be described below with reference to the drawings. An example in which the frequency converter **100** is applied to a receiver RX will be discussed here.

The frequency converter **100** shown in FIG. **1** forms the receiver RX together with an antenna **101**. The frequency converter **100** is disposed at a radio frequency stage of the receiver RX which receives an RF signal S_{RF} output from the antenna **101**, and has a function of converting a frequency f**1** of the RF signal S_{RF} into a desired frequency of a multiplication signal S**3**. In one example, the frequency converter **100** includes the mixer **1**, an amplifier **11**, a signal generator **12**, a filter **13**, and output terminals **14***a* and **14***b* (hereafter also be referred to as an "output terminal **14**" if it is not necessary to distinguish the output terminals **14***a* and **14***b* from each other). The amplifier **11** receives and amplifies the RF signal S_{RF} and outputs the amplified RF signal S_{RF} as a signal S**1** (first high frequency signal). The signal generator **12** functions as a so-called local oscillator and generates a local signal (second high frequency signal) S**2** having a frequency f**2**. In one example, the signal generator **12** generates and outputs a local signal S**2** of −15 dBm±5 dBm. The signal S**1** and the local signal S**2** generated as described above are transmitted to an impedance circuit **4** via a signal transmission line (for example, a microstrip line, hereinafter may also be referred to as a "transmission line") L**1** whose characteristic impedance is defined as 50 Ω.

The mixer **1** includes a magnetoresistance effect element **2**, a magnetic-field applying unit **3**, the impedance circuit **4**, and an impedance conversion circuit **5**. The mixer **1** multiplies the signal S**1** (frequency f**1**) output from the amplifier **11** by the local signal S**2** (frequency f**2**) generated by the signal generator **12**, and outputs an output signal S**5** as multiplication signals. In this case, the output signal S**5** includes a signal of the frequency f**1**, a signal of the frequency f**2**, and multiplication signals of frequencies (f**1**+f**2**), (f**1**−f**2**), 2×f**1**, 2×f**2**, 3×f1, 3×f2, and so on. The signal generator **12** is not an essential component for the frequency converter **100**, and a signal generated by the signal generator **12** may be input, as well as the RF signal S_{RF}, from the outside of the frequency converter **100**. The mixer **1** shown in FIG. **1** is represented by an equivalent circuit, such as that shown in FIG. **2**.

In this embodiment, by using an evaluation based circuit board EC shown in FIG. **3**, the voltage signal S**4** generated in the mixer **1** was evaluated. This evaluation based circuit board EC includes: a network analyzer (made by Agilent Technologies, Inc. model name 8720ES) **51** that generates and outputs a signal S**1**; a signal generator (made by Agilent Technologies, Inc. model name 83620B), which is used as the signal generator **12**, that generates and outputs a local signal S**2**; a BNC terminal **52** which is connected to the network analyzer **51** and the signal generator **12** with a coaxial cable and which is also connected to a transmission line L**1** and outputs the signals S**1** and S**2** to the transmission line L**1**; the transmission line L**1** formed of a microstrip line and connecting the BNC terminal **52** and a capacitor **4***a*; the capacitor **4***a* (made by TDK Corporation: **1005** chip capacitor (4 pF)); a transmission line Lm formed of a microstrip line and connecting the capacitor **4***a* and a magnetoresistance effect element **2**; the magnetoresistance effect element **2** connected between the transmission line Lm and a ground plane **53** with a bonding wire **54**; and a filter **13** which is formed as a cut filter using a λ/4 stub line **55** connected to the transmission line Lm and a sector λ/4 stub **56** connected to the λ/4 stub line **55** and which outputs the voltage signal S**4**. In the λ/4 stub line **55** and the sector λ/4 stub **56**, λ is a wavelength of the local signal S**2** (frequency f**2**). Among the above-described frequency components included in the signals generated by the magnetoresistance effect element **2**, the signal levels of the frequency components f**1** and f**2** are much higher than those of the other frequency components (f**1**+f**2**), (f**1**−f**2**), 2×f**1**, 2×f**2**, 3×f**1**, 3×f**2**, and so on, and thus, it is necessary to attenuate the frequency components f**1** and f**2**. In this case, the frequency f**1** of the signal S**1** is close to the frequency f**2** of the local signal S**2**. Thus, the length λ/4 of a resonator which attenuates the local signal S**2** is set as a length effective in attenuating both the frequency components f**1** and f**2**.

The magnetoresistance effect element **2** installed in this evaluation based circuit board EC is configured such that a magnetization component in a direction perpendicular to the film surface direction is applied from the magnetic-field applying unit **3** to the magnetoresistance effect element **2**. FIG. **4** illustrates a result of comparing a spectrum waveform of resonance characteristics of the magnetoresistance effect element **2** obtained when a magnetic field H is applied to the free magnetization layer **21** of the magnetoresistance effect element **2** in a film surface direction with a spectrum waveform of resonance characteristics of the magnetoresistance effect element **2** obtained when the magnetic field H is applied in a direction perpendicular to the film surface direction. When the magnetic field H is applied in a direction perpendicular to the film surface, resonance characteristics having a high Q factor are obtained, and a high multiplication signal can be output. Moreover, by adjusting the magnetic field H generated from the magnetic-field applying unit **3** to tilt at an angle of 5° to 175° from the film surface direction toward a direction perpendicular to the film surface direction with respect to the free magnetization layer **21** of the magnetoresistance effect element **2**, the magnetoresistance effect element **2** can obtain resonance characteristics having an even higher Q factor, and the highest multiplication signal can be obtained. The Q factor of 100 or higher makes it possible to considerably increase reception performance (sensitivity and frequency selectivity). Thus, the magnetoresistance effect element **2** can be used as a mixer having a band-pass filter function.

FIG. **5** shows resonance characteristics of the magnetoresistance effect element **2** obtained when a magnetic field H applied to the magnetoresistance effect element **2** is maintained at a fixed value and spectrum waveforms of a first high frequency signal S**1** (frequency f**1**) and a second high frequency signal S**2** (frequency f**2**) for a local signal within a region of a resonant frequency f**0** of the resonance characteristics. When the resonant frequency f**0** of the magnetoresistance effect element **2** is set to coincide with the resonant frequency f**2** of the second high frequency signal S**2** for a local signal and when the frequency f**1** of the first high frequency signal S**1** is normally set to be near the frequency f**2**, the multiplication signal is maximized. As the frequency f**1** of the first high frequency signal S**1** deviates from the frequency f**2**, the resonance characteristics decrease, and accordingly, the multiplication signal gradually attenuates. In accordance with the frequency conversion operation of the magnetoresistance effect element **2**, an attenuation operation, that is, the same effect (frequency selective attenuator of the present invention) as that when a band-pass filter is inserted can be obtained. As a square law detection output generated by the magnetoresistance effect element **2**, frequencies (f**1**+f**2**), (f**1**−f**2**), 2×f**1**, 2×f**2**, 3×f**1**, 3×f**2**, and so on, of the multiplication signals are generated. In FIG. **5**, however, only (f**1**+f**2**) and (f**1**−f**2**) are shown.

FIG. **6** shows resonance characteristics of the magnetoresistance effect element **2** obtained when a magnetic field H applied to the magnetoresistance effect element **2** is maintained at a fixed value and spectrum waveforms of a first high frequency signal S**1** (frequency f**1**) and a second high frequency signal S**2** (frequency f**2**) for a local signal within a region of a resonant frequency f**0** of the resonance characteristics. By fixing the strength of a magnetic field to be applied, the resonant frequency f**0** of the magnetoresistance effect element **2** is fixed, and multiple spectrum waveforms of the first high frequency signal S**1** (frequency f**1**) and the second high frequency signal S**2** (frequency f**2**) for a local signal are shown within a region of the resonant frequency f**0**. The spectrum waveforms show the relationships between the frequencies and the resonance characteristics when f**1** and f**2** take values of 3 GHz and 3.05 GHz, respectively, and when f**1**' and f**2**' take values of 3.5 GHz and 3.55 GHz, respectively, when f**1**' and f**2**" take values of 4 GHz and 4.05 GHz, respectively, and when f**1**''' and f**2**''' take values of 4.5 GHz and 4.55 GHz, respectively. In particular, by providing a fixed frequency difference between the first high frequency signal S**1** (frequency f**1**) and the second high frequency signal S**2** (frequency f**2**) for a local signal, the spectrum waveform of the multiplication signal (f**1**−f**2**) is set to appear the same position. As the frequency deviates from the resonant frequency f**0** of the magnetoresistance effect element **2**, the multiplication signal gradually attenuates. In accordance with the frequency conversion operation of the magnetoresistance effect element **2**, an attenuation operation, that is, the same effect (frequency selective attenuator of the present invention) as that when a band-pass filter is inserted can be obtained. As a square law detection output generated by the magnetoresistance effect element **2**, frequencies (f**1**+f**2**), (f**1**−f**2**), 2×f**1**, 2×f**2**, 3×f**1**, 3×f**2**, and so on, of the multiplication signals are generated. In FIG. **6**, however, only the multiplication signal (f**1**−f**2**) as a square law detection output generated by the magnetoresistance effect element **2** is shown.

According to the evaluations obtained by using the evaluation based circuit board EC of this embodiment, when a signal S1 having a signal level of −15 dBm (frequency f1=3.05 GHz) and a local signal S2 having a signal level of −15 dBm (frequency f2=3.0 GHz) are input, as shown in FIG. 7*a*, the magnetoresistance effect element 2 is able to generate a voltage signal S4 having a signal level of −65 dBm (a level of frequency (f1−f2)=50 MHz), as shown in FIG. 7*b*, also due to the fact that the impedance of the transmission line Lm is maintained at a high value.

Similarly, by using the evaluation based circuit board EC, when a signal S1 having a signal level of −15 dBm (frequency f1=3.55 GHz) and a local signal S2 having a signal level of −15 dBm (frequency f2=3.5 GHz) are input, as shown in FIG. 8*a*, the magnetoresistance effect element 2 is able to generate a voltage signal S4 having a signal level of −50 dBm (a level of frequency (f1−f2)=50 MHz), as shown in FIG. 8*b*.

Similarly, by using the evaluation based circuit board EC, when a signal S1 having a signal level of −15 dBm (frequency f1=4.05 GHz) and a local signal S2 having a signal level of −15 dBm (frequency f2=4.0 GHz) are input, as shown in FIG. 9*a*, the magnetoresistance effect element 2 is able to generate a voltage signal S4 having a signal level of −42 dBm (a level of frequency (f1−f2)=50 MHz), as shown in FIG. 9*b*.

Similarly, by using the evaluation based circuit board EC, when a signal S1 having a signal level of −15 dBm (frequency f1=4.55 GHz) and a local signal S2 having a signal level of −15 dBm (frequency f2=4.5 GHz) are input, as shown in FIG. 10*a*, the magnetoresistance effect element 2 is able to generate a voltage signal S4 having a signal level of −50 dBm (a level of frequency (f1−f2)=50 MHz), as shown in FIG. 10*b*.

A graph obtained by plotting peak heights appearing in the spectrum waveforms of the voltage signal S4 (a level of frequency (f1−f2)=50 MHz) when f1 and f2 of the signal S1 (frequency f1) and the local signal S2 (frequency f2) are set to be 3 GHz and 3.05 GHz, respectively, 3.5 GHz and 3.55 GHz, respectively, 4.0 GHz and 4.05 GHz, respectively, and 4.5 GHz and 4.55 GHz, respectively, is shown in FIG. 11. This change in the magnitude of the voltage signal S4 indicates frequency selectivity corresponding to the resonance characteristics of the magnetoresistance effect element 2. In this example, when the frequency peak of the resonance characteristics of the magnetoresistance effect element 2 is 4 GHz, if the first high frequency signal S1 and the second high frequency signal S2 for a local signal at near 4 GHz, which is the same as the frequency peak of the magnetoresistance effect element 2, are input, the voltage signal S4 exhibits the maximum strength, and if the first high frequency signal S1 and the second high frequency signal S2 deviate from 4 GHz, the voltage signal S4 attenuates. That is, the same effect as that when the signals pass through a band-pass filter having a maximum strength peak at 4 GHz can be obtained. These band-pass filter characteristics generated by a square law detecting operation (mixing operation) performed by the magnetoresistance effect element 2 produce a great influence on the Q factor of the resonance characteristics and the level of a multiplication signal. Since the magnetic field H is applied to the free magnetization layer 21 of the magnetoresistance effect element 2 in a direction perpendicular to the film surface of the free magnetization layer 21, resonance characteristics having a high Q factor can be obtained, and the above-described band-pass filter characteristics having a narrow passband can be obtained. In particular, in order to apply such band-pass filter characteristics to a wireless communication band-pass filter, it is necessary that a band-pass filter implemented by a square law detecting operation (mixing operation) performed by the magnetoresistance effect element 2 achieve a Q factor of 100 or higher and have a narrow passband.

FIG. 12 is an equivalent circuit diagram of a band-pass filter 7 and a mixer 8 produced within the magnetoresistance effect element 2 when the magnetic field H applied to the magnetoresistance effect element 2 is fixed. In FIG. 12, RF In, which is an input terminal for the first high frequency signal S1, Lo In, which is an input terminal for the second high frequency signal S2 for a local signal, and IF Out, which is an output terminal for a multiplication signal are separated. However, in the case of a magnetoresistance effect element, three input/output terminals RF In, Lo In, and IF Out are integrated into one signal line.

In the band-pass filter 7 (frequency selective attenuator of the present invention) shown in FIG. 12, the maximum strength and attenuation of the resonance characteristics of the magnetoresistance effect element 2 are determined by the frequency positions of the first high frequency signal S1 (frequency f1) and the second high frequency signal S2 (frequency f2) for a local signal within a region of the resonance frequency f0 of the resonance characteristics. A typical mixer exhibits flat characteristics for a multiplication signal when the multiplication signal is in the operating frequency region, and outputs the multiplication signal at a fixed magnitude. FIG. 12 shows an equivalent circuit used for generating a multiplication signal of the magnetoresistance effect element 2 and formed as a combination of the band-pass filter 7 and the mixer 8 having flat characteristics.

As the magnetoresistance effect element 2 according to the present invention, the configuration of a TMR element including a free magnetization layer 21 and a pinned magnetization layer 23 magnetized in in-plane directions with respect to a magnetic film surface is shown in FIGS. 13 and 14. More specifically, the magnetoresistance effect element 2 includes the free magnetization layer 21, a spacer layer 22, the pinned magnetization layer 23, and an antiferromagnetic layer 24. In the state in which the layers are stacked on each other in this order, the free magnetization layer 21 and the antiferromagnetic layer 24 are disposed between an upper electrode 25 and a lower electrode 26 such that the free magnetization layer 21 is connected to the upper electrode 25 with a cap layer 25*a* and one via-hole therebetween and such that the antiferromagnetic layer 24 is connected to the lower electrode 26 with a cap layer 26*a* and another via-hole therebetween. Via-holes connected to the upper electrode 25 and the lower electrode 26 are not shown in FIG. 1. In this case, the free magnetization layer 21 is formed of a ferromagnetic material as a magnetosensitive layer. The spacer layer 22 is a non-magnetic spacer layer formed of a non-magnetic material having insulation properties, and serves as a tunnel barrier layer. The spacer layer 22 is formed, generally, with a thickness of 1 nm or smaller. The lower electrode 26 is connected to a ground. As a material of the free magnetization layer 21 and the pinned magnetization layer 23, a magnetic metal, such as Fe (iron), Co (cobalt), Ni (nickel), and Cr (chrome), or a magnetic alloy thereof is used. Further, an alloy obtained by mixing B (boron) into a magnetic alloy for decreasing saturation magnetization may be used.

In one example, the pinned magnetization layer 23 includes, as shown in FIG. 13, a ferromagnetic layer (second magnetic layer) 23*a* in which a magnetization direction is fixed, a non-magnetic layer 23*b* formed of a metal, such as Ru (ruthenium), and another ferromagnetic layer (first magnetic layer) 23*c* in which a magnetization direction is fixed opposite to that of the ferromagnetic layer 23*a*. The layers are stacked on each other in this order such that the ferromagnetic layer 23*c* is positioned above the antiferromagnetic layer 24. As the multilayer configuration of the pinned magnetization layer **23**, a multilayer film structure, such as CoFe (cobalt iron)-Ru (ruthenium)-CoFe (cobalt iron), for example, may be used.

Concerning the magnetoresistance effect element **2**, in order to increase the possibility that a greater resonance motion will occur in the free magnetization layer **21**, the size of the free magnetization layer **21** is preferably smaller than a 200 nm square, and the element resistance preferably approximates 50 Ω in terms of a DC resistance in order to provide matching with a high frequency transmission circuit. The tunnel barrier layer **22** is preferably formed of a monocrystal MgOx (001) layer or a polycrystal MgOx (0<x<1) layer in which preferred orientation is observed in a (001) crystal face (hereinafter such a layer will be referred to as an "MgO layer"). Moreover, a CoFeB (cobalt-iron-boron) interlayer (not shown) is preferably disposed between the tunnel barrier layer **22** and the free magnetization layer **21** having a BCC structure (Body-Centered Cubic Lattice), and a CoFeB (cobalt-iron-boron) interlayer (not shown) is preferably disposed between the tunnel barrier layer **22** and the pinned magnetization layer **23** having a BCC structure. By the provision of a CoFeB interlayer, it is expected that a coherent tunneling effect will be implemented, and a high magnetoresistance change rate can be obtained.

Magnetization directions of the free magnetization layer **21** and the pinned magnetization layer **23** of the magnetoresistance effect element **2** which are magnetized in in-plane directions are changed and tilted, as shown in FIG. **15***a* and FIG. **15***b*, due to an influence of an external magnetic field applied in a perpendicular direction with respect to a film surface. As shown in FIG. **15***a*, the magnetization direction of the free magnetization layer **21**, which is almost parallel to the film surface when a perpendicular-to-plane direction magnetic field H is not applied, is sharply tilted from an in-plane direction toward a perpendicular direction when the perpendicular-to-plane direction magnetic field H is applied. As shown in FIG. **15***b*, the magnetization direction of the free magnetization layer **21**, which is almost antiparallel to the film surface when the perpendicular-to-plane direction magnetic field H is not applied, is sharply tilted from the in-plane direction toward a perpendicular direction when the perpendicular-to-plane direction magnetic field H is applied.

As the magnetoresistance effect element **2** according to the present invention, the configuration of a TMR element including a free magnetization layer **21** magnetized in directions perpendicular to a magnetic film surface (a pinned magnetization layer **23** is magnetized in an in-plane direction with respect to the film surface of a magnetic layer) is shown in FIG. **16**. More specifically, the magnetoresistance effect element **2** includes the free magnetization layer **21**, a spacer layer **22**, and the pinned magnetization layer **23**. In the state in which the layers are stacked on each other in this order, the free magnetization layer **21** and the pinned magnetization layer **23** are disposed between an upper electrode **25** and a lower electrode **26** such that the free magnetization layer **21** is connected to a right electrode **26** and that the pinned magnetization layer **23** is connected to a left electrode **25**. In this case, the free magnetization layer **21** is formed of a ferromagnetic material as a magnetosensitive layer. The spacer layer **22** is a non-magnetic spacer layer formed of a non-magnetic material having insulation properties, and serves as a tunnel barrier layer. The spacer layer **22** is formed generally with a thickness of 1 nm or smaller. The lower electrode **25** is connected to a ground.

The free magnetization layer **21** of the magnetoresistance effect element **2** which is magnetized in directions perpendicular to a film surface of a magnetic layer will be discussed below. Concerning the free magnetization layer **21**, for a magnetic material having a high coercive force acting in a direction perpendicular to the film surface of the magnetic layer, the composition ratio of the material is changed, an impurity is added to the material, or the thickness of the material is adjusted, thereby decreasing the coercive force. The free magnetization layer **21** may be formed of, for example, a magnetic material having a small magnetic anisotropic energy density, such as CoFeB (cobalt-iron-boron). In order to increase the possibility that a greater resonance motion will occur in the free magnetization layer **21**, the size of the free magnetization layer **21** is preferably smaller than a 200 nm square, and the element resistance preferably approximates 50 Ω in terms of a DC resistance in order to provide matching with a high frequency transmission circuit. The tunnel barrier layer **22** is preferably formed of monocrystal MgOx (001), and adjustments are more preferably made so that a coherent tunneling effect will be implemented between the tunnel barrier layer **22** and the free magnetization layer **21**, and then, a high magnetoresistance change rate can be obtained.

The magnetic-field applying unit **3** includes, as shown in FIG. **1**, wiring **31** for magnetic-field generation, a magnetic yoke **32**, and a current supply unit **33**. The wiring **31** for magnetic-field generation is disposed, as shown in FIG. **17**, above the magnetoresistance effect element **2** with the upper electrode **25** therebetween. The magnetic yoke **32** includes an apex magnetic body **32***a*, lateral magnetic bodies **32***b* and **32***c*, lower magnetic bodies **32***d* and **32***e*, and bottom magnetic bodies **32***f* and **32***g*. In this case, the apex magnetic body **32***a* is disposed above the wiring **31** for magnetic-field generation. The lateral magnetic body **32***b* is disposed on one side (for example, a right side in FIG. **17**) of the wiring **31** for magnetic-field generation and is connected to the apex magnetic body **32***a*. The lateral magnetic body **32***c* is disposed on the other side (for example, a left side in FIG. **17**) of the wiring **31** for magnetic-field generation and is connected to the apex magnetic body **32***a*. The lower magnetic body **32***d* is disposed on one side (for example, a right side in FIG. **17**) of the magnetoresistance effect element **2** and is connected to the lateral magnetic body **32***b*. The lower magnetic body **32***e* is disposed on the other side (for example, a left side in FIG. **17**) of the magnetoresistance effect element **2** and is connected to the lateral magnetic body **32***c*. With this configuration, the lower magnetic body **32***e*, the lateral magnetic body **32***c*, the apex magnetic body **32***a*, the lateral magnetic body **32***b*, and the lower magnetic body **32***d* are interconnected to each other in this order, and are formed, as a whole, in a strip-like shape. They are also disposed above the magnetoresistance effect element **2**, as shown in FIG. **1**, such that they stretch over the wiring **31** for magnetic-field generation.

The bottom magnetic body **32***f* is disposed, as shown in FIG. **17**, under the lower magnetic body **32***d* in a state in which it is connected to the lower magnetic body **32***d*. An edge portion of the bottom magnetic body **32***f* facing the magnetoresistance effect element **2** advances between the upper electrode **25** and the lower electrode **26** of the magnetoresistance effect element **2** in a state in which it is insulated from the upper electrode **25** and the lower electrode **26**, and reaches an area near one lateral surface of the free magnetization layer **21** of the magnetoresistance effect element **2**. The bottom magnetic body **32***g* is disposed under the lower magnetic body **32***e* in a state in which it is connected to the lower magnetic body **32***e*. An edge portion of the bottom magnetic body **32***e* facing the magnetoresistance effect element **2** also advances between the upper electrode **25** and the lower electrode **26** of the magnetoresistance effect element **2** in a state in which it is insulated from the upper electrode **25** and the lower electrode **26**, and reaches an area near the other lateral surface of the free magnetization layer **21** of the magnetoresistance effect element **2**.

With the above-described configuration, when a current I flows through the wiring **31** for magnetic-field generation, the magnetic yoke **32** forms a closed magnetic circuit for a magnetic field generated around the wiring **31** for magnetic-field generation, and applies a magnetic field H to the free magnetization layer **21** of the magnetoresistance effect element **2** disposed in an area, which is a gap of this closed magnetic circuit (a gap between the pair of bottom magnetic bodies **32***f* and **32***g*), as shown in FIG. **17**. It is noted that a cap layer **25***a* for electrically connecting the free magnetization layer **21** of the magnetoresistance effect element **2** and the upper electrode **25** and one via-hole are disposed, and a cap layer **26***a* for electrically connecting the antiferromagnetic layer **24** and the lower electrode **26** and the other via-hole are disposed. In this example, the above-described wiring **31** for magnetic-field generation and magnetic yoke **32** of the magnetic-field applying unit **3** are formed on a silicon wafer by using a known semiconductor manufacturing process. Similarly, the magnetoresistance effect elements **2** are formed on a silicon wafer by using a known semiconductor manufacturing process and are individually cut. The magnetoresistance effect element **2** is disposed in a gap between the bottom magnetic bodies **32***f* and **32***g* of the magnetic yoke **32**. The magnetoresistance effect element **2** is rotated so as to increase or decrease a tilting angle θ between the direction of the magnetic field H and the direction of the film surface of the free magnetization layer **21**, as indicated by θ in FIG. **18**, thereby making it possible to change and tilt a relative angle of the magnetoresistance effect element **2** to the magnetic field H. The magnetoresistance effect element **2** is disposed so that, by providing a magnetic component in a direction perpendicular to the film surface to the free magnetization layer **21**, the Q factor of resonance characteristics of the magnetoresistance effect element **2** can be increased.

The current supply unit **33** is connected to both end portions of the wiring **31** for magnetic-field generation extending from both lateral sides of the apex magnetic body **32***a*, and supplies a current I to the wiring **31** for magnetic-field generation. The current supply unit **33** is configured such that it can change a value of the current I. Accordingly, by changing the value of the current I output from the current supply unit **33**, the magnetic-field applying unit **3** changes the strength of the magnetic field H to be applied to the magnetoresistance effect element **2**, thereby making it possible to change the resonant frequency f**0** of the magnetoresistance effect element **2**. In this example, only one piece of wiring **31** for magnetic-field generation which passes through the inside of the magnetic yoke **32** is provided. However, by forming the wiring **31** for magnetic-field generation in a coil-like shape, a plurality of pieces of wiring for magnetic-field generation which pass through the inside of the magnetic yoke **32** may be provided, thereby increasing the strength of the magnetic field H.

In the impedance circuit **4**, the impedance (input/output impedance) for a voltage signal (multiplication signal) S**4**, which will be discussed, is higher than the impedance (input/output impedance) for the signals S**1** and S**2**. The impedance circuit **4** is disposed between the above-described transmission line L**1** (input transmission line) having characteristic impedance of 50 Ω and a transmission line Lm having characteristic impedance of 50 Ω and being connected to the magnetoresistance effect element **2** such that the impedance circuit **4** is fit in a small gap formed between the transmission lines L**1** and Lm. In this case, in the impedance circuit **4**, the impedance for the signals S**1** and S**2** transmitted through the transmission line L**1** is lower than the characteristic impedance (50Ω) of the transmission line L**1**, and the signals S**1** and S**2** are output from the transmission line L**1** to the transmission line Lm through the use of the low impedance for the signals S**1** and S**2**. That is, the impedance circuit **4** serves as an impedance element which provides a low input/output impedance for signals of a frequency band including the signals S**1** and S**2**, and allows the signals S**1** and S**2** to pass through the impedance circuit **4** such that the attenuation of the amplitude of the signals S**1** and S**2** is contained to a minimal level. In contrast, in the impedance circuit **4**, the impedance for a signal of a square law detection output (which is a multiplication signal, that is, the voltage signal S**4** of a frequency (f**1**±f**2**)) generated in the magnetoresistance effect element **2** is set such that the impedance as viewed from the magnetoresistance effect element **2** (input/output impedance) will be the impedance (preferably the impedance of 500 Ω or higher) higher than the characteristic impedance (50Ω) of the transmission lines L**1** and Lm.

In the mixer **1**, the resonant frequency f**0** of the magnetoresistance effect element **2** is set to match the frequency f**2** of the local signal S**2**, and also, the frequency f**1** of the signal S**1** is generally set to be a frequency near the frequency f**2**, which will be discussed later. Accordingly, in one example, the impedance circuit **4** may be formed as a band-pass filter having impedance characteristics shown in FIG. **19** or as a high-pass filter shown in FIG. **20**. In this case, this band-pass filter is restricted to have impedance characteristics in which, as shown in FIGS. **19** and **20**, the resonant frequency f**0** of the magnetoresistance effect element **2** (the frequency f**2** of the local signal S**2**) and the frequency f**1** of the signal S**1** are included in a passband and frequencies (f**1**+f**2**), (f**1**−f**2**), 2×f**1**, 2×f**2**, 3×f**1**, 3×f**2**, and so on, of multiplication signals generated in the magnetoresistance effect element **2** as a square law detection output are included in an attenuation band. The impedance circuit **4** also includes, for example, a coupling capacitor, and has a function of preventing DC components of a square law detection output generated in the magnetoresistance effect element **2** from leaking to the amplifier **11** or the signal generator **12**.

In one example, the impedance conversion circuit **5** includes an operational amplifier **5***a*. In this example, the operational amplifier **5***a* functions as a differential amplifier with one input terminal of the operational amplifier **5***a* being connected to the upper electrode **25** and the other input terminal thereof being connected to a ground. With this configuration, the operational amplifier receives the voltage signal S**4** which has been generated across the magnetoresistance effect element **2** from the input of the signal S**1** and the local signal S**2** via a capacitor **4***a*, amplifies the voltage signal S**4**, and outputs the amplified voltage signal as the output signal S**5** to an output transmission line L**2** (for example, a microstrip line, and hereinafter also referred to as a "transmission line L**2**"). The operational amplifier **5***a* generally has characteristics in which the input impedance is very high and the output impedance is sufficiently low. Accordingly, with this configuration, the operational amplifier **5***a* receives the voltage signal S**4** generated across the magnetoresistance effect element **2** with the input impedance higher than the output impedance, amplifies the received voltage signal S**4** to the output signal S**5**, and outputs the output signal S**5** with the low impedance. Thus, the operational amplifier **5***a* serves as an impedance converter. In this case, the operational amplifier **5***a* outputs the output signal S**5** with the output impedance which matches the characteristic impedance of the output transmission line L2. In one example, the filter **13** is formed as a band-pass filter (BPF: second filter) and is disposed in the transmission line L2. The filter **13** allows a signal only having a desired frequency to pass through the filter **13**, thereby outputting the signal as the multiplication signal S3 to the output terminal **14**. More specifically, the filter **13** allows a signal having one (desired frequency) of the frequencies (f1−f2) and (f1+f2) to pass through the filter **13**.

A description will now be given of a mixing operation of the mixer **1** and a frequency conversion operation of the frequency converter **100**. In one example, an RF signal S_{RF} received via the antenna **101** (frequency f1=4.05 GHz) is input, and the signal generator **12** generates a local signal S2 (frequency f2=4.0 GHz (<f1)). The impedance circuit **4** includes a chip capacitor **4***a*, which is the least expensive one, and the frequencies f1 and f2 of the signals S1 and S2, respectively, are included in the passband of the impedance circuit **4**. Additionally, as shown in FIG. **12**, it is preferable that the resonance characteristics of the magnetoresistance effect element **2** are maximized with respect to the frequency f2 of the local signal S2. Thus, the value of the current I to be supplied from the current supply unit **33** to the wiring **31** for magnetic-field generation is set to be a value which allows a magnetic field H that causes the resonant frequency f0 to coincide with the frequency f2 of the local signal S2 to be applied to the magnetoresistance effect element **2**. Power of the local signal S2 is set to be power (for example, −15 dBm±5 dBm) which is capable of supplying a current that can generate resonance in the magnetoresistance effect element **2**. The output signal S5 output from the differential amplifier **5** as a result of the mixing operation of the mixer **1** includes frequency components (f1, f2) of the signals S1 and S2, respectively, and frequency components ((f1+f2), (f1−f2), 2×f1, 2×f2, 3×f1, 3×f2, and so on) of the multiplication signals. Among these frequency components, the filter **13** may allow a desired frequency component (a frequency component (f1+f2) or a frequency component (f1−f2)) to pass through the filter **13**. In this example, the filter **13** is configured such that it allows a lower frequency component (f1−f2) to pass through the filter **13** and stops the signals having the other frequency components from passing through the filter **13**. In this case, the filter **13** is formed as a band-pass filter. However, the filter **13** may be formed as a low-pass filter.

In this frequency converter **100**, in a state in which the current I is being supplied from the current supply unit (a state in which the magnetic field H is being applied to the magnetoresistance effect element **2**), the local signal S2 (frequency f2) is input from the signal generator **12** to the mixer **1**. In this case, the local signal S2 passes through the impedance circuit **4** (capacitor **4***a*) with a very small attenuation and is output to the magnetoresistance effect element **2**. The local signal S2 is set such that the frequency f2 of the local signal S2 coincides with the resonant frequency f0 of the magnetoresistance effect element **2** and such that power of the local signal S2 causes the magnetoresistance effect element **2** to generate the maximum resonance. At this time, the RF signal S_{RF} (frequency f1) is input from the antenna **101** to the amplifier **11**, and when the amplifier **11** starts to output the signal S1, the magnetoresistance effect element **2** performs a square law detecting operation on the two signals S1 and S2. In this case, the signal S1 passes through the impedance circuit **4** (capacitor **4***a*) with a very small attenuation without being reflected on the impedance circuit **4**, and is output to the magnetoresistance effect element **2**.

In this case, in comparison with a semiconductor pn junction diode, the magnetoresistance effect element **2** performs a square law detecting operation (rectifying operation) in a resonance state with a small forward voltage. Accordingly, even if power of the local signal S2 for generating this forward voltage in the magnetoresistance effect element **2** is smaller than power (for example, 10 dBm) required when a semiconductor pn junction diode is used, the magnetoresistance effect element **2** performs a square law detecting operation so as to multiply the signal S1 by the local signal S2, thereby generating the voltage signal S4 across the magnetoresistance effect element **2**. At this time, even if a DC voltage is generated in the magnetoresistance effect element **2**, the capacitor **4***a* stops the DC voltage from leaking to the antenna or the signal generator **12** (cuts the DC voltage), thereby protecting the antenna and the signal generator **12** as well as the magnetoresistance effect element **2**.

The voltage signal S4 generated by a square law detecting operation (mixing operation) performed by the magnetoresistance effect element **2** is constituted by various frequency components including the two frequency components (f1+f2, f1−f2), as stated above, and these frequency components are frequency components included in the attenuation band, which is out of the passband of the capacitor **4***a*. Accordingly, the impedance of the capacitor **4***a* (that is, the impedance circuit **4**) for the frequency components (f1+f2, f1−f2) is greater than the impedance of the capacitor **4***a* for the signal S1 (frequency f1) and the local signal S2 (frequency f2). In particular, the impedance of the capacitor **4***a* for a frequency component of the same frequency (f1−f2=50 MHz) as that of the multiplication signal S3 output from the frequency converter **100** of this example is a value higher than 1000Ω. Moreover, as stated above, the input impedance of the operational amplifier **5***a* forming the impedance conversion circuit **5** connected to the magnetoresistance effect element **2** is a very high value (generally, several hundreds of KΩ or higher). Accordingly, since the impedance of the transmission line Lm to which the voltage signal S4 is output by the magnetoresistance effect element **2** is a high value (exceeding 1000Ω), the magnetoresistance effect element **2** generates a high level of the voltage signal S4 and outputs it to the transmission line Lm.

In this manner, in the mixer **1** and the frequency converter **100**, the impedance circuit **4** disposed between the transmission line L1 and the magnetoresistance effect element **2** outputs the signal S1 (frequency f1) and the local signal S2 (frequency f2), which are received via the transmission line L1, to the magnetoresistance effect element **2** through the use of the impedance of the impedance circuit **4**, which is lower than the characteristic impedance of the transmission line L1. Thus, the signal S1 and the local signal S2 can be output to the magnetoresistance effect element **2** with only a small attenuation. On the other hand, in a frequency band of the voltage signal (multiplication signal) S4 generated by the magnetoresistance effect element **2**, the output impedance higher than the impedance for the signals S1 and S2 is utilized. Thus, by using the mixer **1** and the frequency converter **100**, since the signal S1 and the local signal S2 can be output to the magnetoresistance effect element **2** with only a small attenuation, the multiplication signal S3 (frequency component (f1−f2)) can be output by mixing (multiplying) the signal S1 with (by) the local signal S2 by using the local signal S2 having lower power, in other words, by multiplying the signal S1 by the local signal S2 by using smaller power. As a result, power saving can further be enhanced. Additionally, since the impedance used in the impedance circuit **4** for the frequency band of the voltage signal (multiplication signal) S4 generated by the magnetoresistance effect element **2** is high, it is possible to prevent a decrease (attenuation) in the voltage signal (multiplication signal) S4 generated by the magnetoresistance effect element **2**, and as a result, a decrease in the output of the multiplication signal S**3** can also be prevented.

The present invention is not restricted to the above-described configuration, and various configurations may be employed. In the above-described example, as the magnetoresistance effect element **2**, a TMR element, such as an MgO-TMR element, is used. However, another magnetoresistance effect element, such as a CPP-GMR (Current-Perpendicular-to-Plane giant magnetoresistance) element, may be used. As the material of the spacer layer **22**, an insulator, a metal, or a semiconductor may be used. For example, as the insulator, MgO, Al2O3, or TiO may be used. As the metal, Cu, Ag, Au, Cr, or an alloy material including at least one of these elements may be used. As the semiconductor, an oxide semiconductor may be used, for example, zinc oxide, gallium oxide, tin oxide, indium oxide, or indium tin oxide (ITO) may be used. Films of a spacer layer using a semiconductor are formed such that the above-described oxide semiconductor is sandwiched between first and second non-magnetic films (one of metals Cu, Ag, Au, Cr, and Zn or an alloy thereof).

In the above-described example, the strength of the magnetic field H applied from the magnetic-field applying unit **3** to the magnetoresistance effect element **2** is variable. However, if the frequency f**2** of the local signal S**2** is fixed, the strength of the magnetic field H generated by the magnetic-field applying unit **3** can also be fixed. Accordingly, the magnetic-field applying unit **3** may be constituted by a permanent magnet, so that the strength of the magnetic field can be maintained at a constant value. With this configuration, the magnetic-field applying unit **3** can be formed with a simple structure, thereby making it possible to reduce the manufacturing cost.

REFERENCE SIGNS LIST

1 mixer
2 magnetoresistance effect element
3 magnetic-field applying unit
4 impedance circuit
4*a* capacitor
5 impedance conversion circuit
5*a* operational amplifier
6 resonance characteristics of magnetoresistance effect element
6*a* resonance characteristics of magnetoresistance effect element obtained by the application of magnetic field H in film surface direction
6*b* resonance characteristics of magnetoresistance effect element obtained by the application of magnetic field H in direction perpendicular to film surface direction
7 band-pass filter
8 mixer
11 RF amplifier
12 signal generator for local signal
13 filter
21 free magnetization layer
22 spacer layer
23 pinned magnetization layer
100 frequency converter
H magnetic field
S_{RF} RF signal
S**1** signal
S**2** local signal
S**3** multiplication signal
S**4** multiplication signal output from magnetoresistance effect element
S**5** multiplication signal output from magnetoresistance effect element and amplified by amplifier disposed in the subsequent stage

The invention claimed is:

1. A mixer comprising:

a magnetoresistance effect element that includes a pinned magnetization layer, a free magnetization layer, and a non-magnetic spacer layer disposed between the pinned magnetization layer and the free magnetization layer, and that generates, in response to an input of a first high frequency signal S**1** (frequency f**1**) and a second high frequency signal S**2** (frequency f**2**) for a local signal, a multiplication signal by multiplying both the high frequency signals by each other using a magnetoresistance effect;

a magnetic-field applying unit that applies a magnetic field to the free magnetization layer; and

a frequency selective attenuator that exhibits frequency selectivity for the multiplication signal by using the maximum strength of the multiplication signal generated when a resonant frequency f**0** of the magnetoresistance effect element is set to coincide with the frequency f**2** of the second high frequency signal S**2** for a local signal and when the frequency f**1** of the first high frequency signal S**1** is set to be near the frequency f**2** and by using attenuation of the multiplication signal generated when the first frequency f**1** deviates from the frequency f**2**.

2. The mixer according to claim **1**, wherein there is provided the frequency selective attenuator that exhibits frequency selectivity for the multiplication signal by using, when the resonant frequency f**0** of the magnetoresistance effect element is maintained at a fixed value by applying a constant magnetic field by the magnetic-field applying unit and when the frequency f**2** of the second high frequency signal S**2** for a local signal is set to be near the resonant frequency f**0** of the magnetoresistance effect element and the frequency f**1** of the first high frequency signal S**1** is set to be near the frequency f**2**, attenuation of the multiplication signal generated when the frequency f**1** and the frequency f**2** of the high frequency signals deviate from the resonant frequency f**0** of the magnetoresistance effect element.

3. The mixer according to claim **2**, wherein the magnetoresistance effect element and the magnetic-field applying unit are located so that an angle of the magnetic field generated by the magnetic-field applying unit with respect to a film surface of the free magnetization layer will be an angle tilted in a range of 5° to 175° from a direction of the film surface toward a direction perpendicular to the direction of the film surface.

4. The mixer according to claim **3**, further comprising:

an impedance circuit in which impedance for the multiplication signal is higher than impedance for the first high frequency signal and the second high frequency signal for a local signal, the impedance circuit being disposed between an input transmission line through which the first high frequency signal and the second high frequency signal for a local signal are transmitted and the magnetoresistance effect element, the impedance circuit being constituted by a first filter in which the frequencies of the first high frequency signal and the second high frequency signal for a local signal are included in a passband and frequencies of the multiplication signal are included in an attenuation band, the first filter being constituted by a capacitive element or an active element in which self-resonant frequency band is set to be the passband; and an impedance conversion circuit that inputs the multiplication signal and outputs the multiplication signal with output impedance which matches characteristic impedance of an output transmission line to the output transmission line, input impedance being set to be a value higher than a value of the output impedance.

5. The mixer according to claim **2**, further comprising:

an impedance circuit in which impedance for the multiplication signal is higher than impedance for the first high frequency signal and the second high frequency signal for a local signal, the impedance circuit being disposed between an input transmission line through which the first high frequency signal and the second high frequency signal for a local signal are transmitted and the magnetoresistance effect element, the impedance circuit being constituted by a first filter in which the frequencies of the first high frequency signal and the second high frequency signal for a local signal are included in a passband and frequencies of the multiplication signal are included in an attenuation band, the first filter being constituted by a capacitive element or an active element in which self-resonant frequency band is set to be the passband; and

an impedance conversion circuit that inputs the multiplication signal and outputs the multiplication signal with output impedance which matches characteristic impedance of an output transmission line to the output transmission line, input impedance being set to be a value higher than a value of the output impedance.

6. The mixer according to claim **1**, wherein the magnetoresistance effect element and the magnetic-field applying unit are located so that an angle of the magnetic field generated by the magnetic-field applying unit with respect to a film surface of the free magnetization layer will be an angle tilted in a range of 5° to 175° from a direction of the film surface toward a direction perpendicular to the direction of the film surface.

7. The mixer according to claim **6**, further comprising:

an impedance circuit in which impedance for the multiplication signal is higher than impedance for the first high frequency signal and the second high frequency signal for a local signal, the impedance circuit being disposed between an input transmission line through which the first high frequency signal and the second high frequency signal for a local signal are transmitted and the magnetoresistance effect element, the impedance circuit being constituted by a first filter in which the frequencies of the first high frequency signal and the second high frequency signal for a local signal are included in a passband and frequencies of the multiplication signal are included in an attenuation band, the first filter being constituted by a capacitive element or an active element in which self-resonant frequency band is set to be the passband; and

an impedance conversion circuit that inputs the multiplication signal and outputs the multiplication signal with output impedance which matches characteristic impedance of an output transmission line to the output transmission line, input impedance being set to be a value higher than a value of the output impedance.

8. The mixer according to claim **1**, further comprising:

an impedance circuit in which impedance for the multiplication signal is higher than impedance for the first high frequency signal and the second high frequency signal for a local signal, the impedance circuit being disposed between an input transmission line through which the first high frequency signal and the second high frequency signal for a local signal are transmitted and the magnetoresistance effect element, the impedance circuit being constituted by a first filter in which the frequencies of the first high frequency signal and the second high frequency signal for a local signal are included in a passband and frequencies of the multiplication signal are included in an attenuation band, the first filter being constituted by a capacitive element or an active element in which self-resonant frequency band is set to be the passband; and

an impedance conversion circuit that inputs the multiplication signal and outputs the multiplication signal with output impedance which matches characteristic impedance of an output transmission line to the output transmission line, input impedance being set to be a value higher than a value of the output impedance.

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